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LIFECYCLE COST AND CO_2 EMISSION COMPARISON OF CONVENTIONAL AND RATIONALIZED BRIDGES

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Abstract

The construction industry consumes a great deal of natural resources and energy in constructing, maintaining and demolishing their products such as buildings and bridges. These activities lead significant impacts on global and regional environments in addition to their economic expenses. In this research, the lifecycle cost (LCC) and lifecycle CO_2 ($LCCO_2$) emission of newly developed bridges, including the minimized girder, rationalized box-girder and rationalized truss bridges, are quantified and compared with those of the conventional I-girder, box-girder and truss bridges. It was found that the newly developed types of bridges have lower values in both LCC and $LCCO_2$ than the corresponding conventional bridges do. The effects of span lengths on LCC and $LCCO_2$ are studied for both conventional and rationalized bridges. The characteristics of LCC and $LCCO_2$ are investigated over the lifecycle of a bridge including its construction, maintenance and replacement stages.

KEYWORDS: *lifecycle analysis, lifecycle cost (LCC), lifecycle CO_2 ($LCCO_2$) emission, rationalized bridges, span length*

1. Introduction

Global environment has drawn worldwide attention to reduce the emission of greenhouse gases in recent decades. As a project of international collaboration for the prevention of global warming, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted in May 1992 with the aim of stabilizing the greenhouse gas concentrations in the atmosphere. In the third conference of parties (COP3) of UNFCCC, numerical targets for reducing greenhouse gas emissions by industrial nations are proposed as the Kyoto protocol (UNFCCC 1997). Most industrialized nations are required to reduce the greenhouse gas emissions by a certain percentage of the 1990 level in 2012. For example, Japan has proposed to reduce the greenhouse gas emission by 6%. This proposal urges every industrial nation towards finding effective ways of reducing greenhouse gases emissions from all sectors of the national development. Since the construction industry is one major sector of national development, there will be pressure on the construction industry to find ways of reducing its share of greenhouse

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gases emissions. Due to the use of the construction materials and equipment, and the consumption of the fossil fuels during the related industrial activities, the emissions of greenhouse gases are caused from construction activities. The construction sector is mainly associated with the natural resources consumption and industrial activities, and the major greenhouse gas from this sector is CO_2. Therefore, it is a challenging task for civil engineers to minimize the lifecycle CO_2 ($LCCO_2$) of civil infrastructures as well as their lifecycle costs (LCC).

In recent years, new types of bridges have continued to appear with the development of construction technologies and functional requirements in Japan (JASBC 2003). These include the minimized girder bridges, the rationalized box-girder bridges, and the rationalized truss bridges, which are evolved from the conventional I-girder, box-girder and truss bridges respectively. In a previous research project, a lifecycle assessment method was established for evaluating the technology development of minimized girder bridges (Itoh et al. 2001b). In this research, that method will be extended to all three types of rationalized bridges to quantify their LCC and $LCCO_2$ values. Furthermore, these values are compared with those of the corresponding conventional types of bridges. Studies are also carried out to quantify the effects of span lengths on LCC and $LCCO_2$ of all types of bridges. Finally, the characteristics of LCC and $LCCO_2$ are investigated over the lifecycle of a bridge including its construction, maintenance and replacement stages.

2. Needs and Development of New Types of Bridge

The bridge construction in Japan increased rapidly from the first five-year highway construction plan that started in 1954, and gradually decreased from the later half of the 1970s. During the period from 1956 to 1975, about 61,000 highway bridges were built, which were almost the half of the existing bridges (Nishikawa 1994). Giving that the service life of a bridge is 50 years, a number of bridges are predicted to accept major rehabilitation or replacement in the following decades (Liu and Itoh 1997). It was predicted in the White Paper on Construction of Japan that the maintenance cost of all civil infrastructure systems will increase to about 50% of total public works investment up to 2020 (*White* 1994). The infrastructure finance will soon provide a challenging task for the bridge engineers, and the bridge engineers should pay more attention to the development of bridge technologies to prolong the service life of a bridge. Under such a circumstance, the bridge engineers in Japan have developed three new types of bridges in recent years, including the minimized girder, rationalized box-girder and rationalized truss bridges (JASBC 2003).

2.1 Minimized Girder Bridges

The minimized girder bridge is a newly developed type of bridges. It was first constructed in the second expressway between Tokyo and Nagoya in Japan in 1994 (EXTEC 1995). The major idea of the minimized girder bridge is to reduce the numbers of main girders and secondary girders by rationalizing the bridge structural components such as by increasing the rigidity of the deck. A board of investigation and study comprising near 50 bridge experts including the first author of this paper from both sides of universities and bridge corporations was founded in 1994 to service for the design, construction and service monitoring of this expressway. Figure 1 shows the conceptual graphs of a conventional bridge (abbreviated as CIB below) and a minimized girder bridge (abbreviated as MGB below). The bridge decks are made from prestressed concrete (PC) to enlarge their span lengths. Four main girders are needed if a conventional bridge is designed and constructed, while a minimized girder bridge is constructed with only two main girders in practice. The transverse minor girders and other components are significantly simplified.

a) conventional I-girder bridge (CIB) b) minimized girder bridge (MGB)

Figure 1. Conceptual Graphs of a Conventional I-girder Bridge and a Minimized Girder Bridge

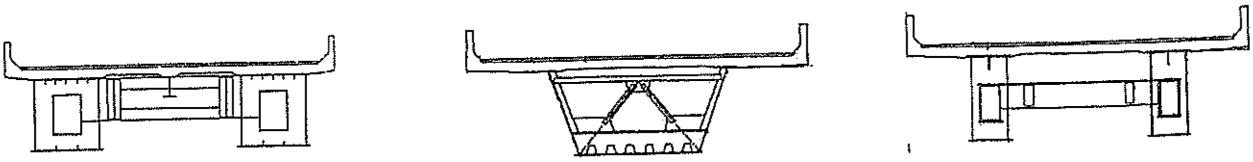
According to the statistics and reports from the fabrication factories and the construction sites, during the fabrication and construction stage of a conventional bridge and a minimized girder bridge, the steel weight, the number of larger components, the number of small components, the weld length and the painting area of a minimized girder bridge are as low as around 95%, 40%, 60%, 40%, and 60% of a conventional bridge, respectively. These percentage values are shown in Table 1. In particular, the number of large components of a minimized girder bridge decreases a lot due to the reduced number of main girders. Furthermore, the span length of a minimized girder bridge may be enlarged to 90 meter (m) from 30~60m of a conventional I-girder bridge.

Table 1. Material Consumption Ratios of a Rationalized Bridge to Its Conventional Bridge

	Steel Weight	Large Components	Small Components	Weld Length	Painting Area
MGB/CIB	95%	40%	60%	40%	60%
RBB1/CBB	70%	35%	30%	45%	55%
RBB2/CBB	90%	45%	55%	70%	65%
RTB/CTB	95%	40%	60%	70%	80%

2.2 Rationalized Box-girder Bridges

The conventional box-girder bridges (abbreviated as CBB below) have been evolved to two types of rationalized box-girder bridges, namely the open cross-section box-girder bridge (abbreviated as RBB1 below) and the narrow box-girder bridge (abbreviated as RBB2 below). Figure 2 shows the conceptual graphs of these three types of bridges. The top flange of RBB1 is similar to an I-girder bridge. Its steel box-girder has an open cross section and a reverse trapezoid shape. The composite box girder is fabricated with the PC decks as a whole and the transverse components are highly excluded.



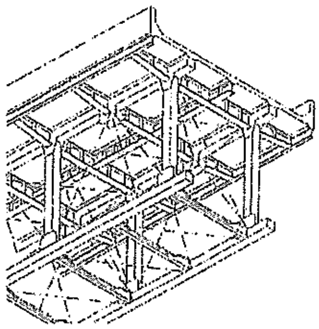
a) conventional box-girder bridge (CBB) b) open cross-section box-girder bridge (RBB1) c) narrow box-girder bridge (RBB2)

Figure 2. Conceptual Graphs of Conventional and Rationalized Box-girder Bridges

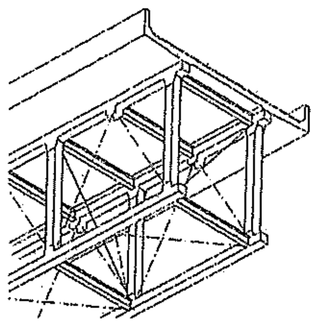
Similar to a minimized girder bridge, a narrow box-girder bridge is constructed with PC decks and its transverse components are simplified. Its main longitudinal girders have a box shape, not the I shape of a minimized girder bridge. The materials consumptions of both RBB1 and RBB2 are also summarized in Table 1 in terms of their ratios to a conventional box-girder bridge. Among all five material consumption criteria listed in Table 1, RBB1 consumes fewer materials than RBB2 does. Furthermore, the standard span lengths of RBB1 and RBB2 are 50-90m and 60-100m respectively, which are bigger than that of CBB, namely 40-80m.

2.3 Rationalized Truss Bridges

Figure 3 conceptually compares a conventional truss bridge (abbreviated as CTB below) and a rationalized truss bridge evolved from it (abbreviated as RTB below). The PC decks adopted in RTB are able to reduce the amounts of the main longitudinal girders and brackets. Therefore, the materials required to construction a rationalized truss bridges are reduced drastically as given in Table 1. The standard span length of a conventional truss bridge is from 60 to 110m, but a rationalized truss bridge can be constructed in 80-150m as its standard span.



a) conventional truss bridge (CTB)



b) rationalized truss bridge (RTB)

Figure 3. Conceptual Graphs of Conventional and Rationalized Truss Bridges

3. Lifecycle Cost and CO_2 Analysis Framework for Bridges

3.1 Bridges Selected for Analysis

In order to study the lifecycle performances of newly developed types of bridges, two I-girder (CIB and MGB), three box-girder (CBB, RBB1 and RBB2) and two truss (CTB and RTB) bridges are formulated. All bridges are assumed with the comparably environmental conditions and they are all 3-span continuous non-composite steel bridges. The widths of all bridges are 10.5m, but their lengths are different because of their different individual standard span lengths.

Some data of the selected conventional and the minimized girder bridge are shown in Table 2. The numbers of their main girders are four and two respectively. The LCC and $LCCO_2$ of both bridges are calculated for the four span lengths from 30 to 60m with an interval of 10m. The span ranges of conventional bridge and the newly developed ones are made the same for comparison, where as the span length of the minimized girder bridge can be extended to 90m. Table 2 also shows the data of the conventional box-girder bridge, and two types of rationalized box girder bridges namely the open cross-section and narrow box-girder bridges too. The span lengths of bridges are set equal to each other for comparison. The mostly adopted composite deck is selected for the rationalized bridges, and RC deck is for the conventional bridges. This table also shows the data of the conventional truss bridge and the rationalized truss bridge. Although the rationalized bridge is a form usually adopted as the bridge of long span, its maximum is set as 100m for comparison with the conventional bridge. It should be noted that all these bridges and their data are assumed by referring to practical bridges as well as publications (for example, JASBC 2001), but these bridges and the following analyses do not reflect any real-world engineering projects.

Table 2. Bridge Data for the Lifecycle Analysis

	I-girder bridges		Box-girder bridges			Truss bridges	
	CIB	**MGB**	**CBB**	**RBB1**	**RBB2**	**CTB**	**RTB**
Span length (m)	30~60	30~60	50~80	60~80	60~80	60~100	80~100
Bridge length (m)	90~180	90~180	150~240	180~240	180~240	180~300	240~300
Deck type	RC	precast PC	RC	composite deck	composite deck	RC	precast PC

3.2 Lifecycle Analysis Approach for Bridges

The lifecycle analysis has played an important role in the bridge management by considering all bridge lifecycle stages at the same time. In this research, the bridge lifecycle contains the construction, maintenance and replacement stages only, and therefore the lifecycle environmental impact and cost could be summed as follows:

$$E_t = E_c + E_m + E_r \tag{1}$$

$$C_t = C_c + C_m + C_r \tag{2}$$

where, E_t and C_t are the environmental impact and cost within the whole lifecycle of a bridge, respectively; E_c and C_c are the environmental impact and cost from the construction stage, respectively; E_m and C_m are the environmental impact and cost from the maintenance stage, respectively; and E_r and C_r are the environmental impact and cost from the replacement stage, respectively.

3.2.1 Cost and CO_2 emission in the construction stage

The environmental impact from the construction stage contains the environmental impact from both the construction materials and the construction machine, and can be formulated in the following equation:

$$E_c = \sum_{n=1}^{N} M_n \times U_{CO_2}(n) + \sum_{j=1}^{J} (G(j) \times U_g(j) + W_w(j) \times U_w(j)/W_l(j)) \times W_h(j) \tag{3}$$

where, M_n and $U_{CO2}(n)$ are the quantity of one kind of construction material (n) and the CO_2 emission due to its consumption per unit; $G(j)$, $U_g(j)$ and $W_h(j)$ are the energy consumption per hour, the CO_2 emission due to the consumption of energy per unit, and the working hours for one construction machine (j); and $W_w(j)$, $U_w(j)$ and $W_l(j)$ are the weight, the CO_2 emission per weight, and the service life for one construction machine (j), respectively. The symbols N and J are the numbers of kinds of materials and machine, respectively.

The volume or weight of materials is calculated for a bridge lifecycle based on the design manuals and interview with bridge engineers. Similarly, the duration of construction equipment used in various construction, maintenance and replacement activities are found by the databases depicting the past experiences and interview. The CO_2 emission from the unit volume or the unit weight or the unit duration is taken from the results of studies by PWRI (1994) and JSCE (1997). The PWRI values are obtained by input-output analysis of Japan. The JSCE values are calculated with LCA method in which all processes are accounted for making a product. This LCA method is supplemented by the input-output analysis. Since JSCE values are new and cross-checked with both LCA and the input-output analysis, the JSCE values are used in this research to calculate the lifecycle environmental impact of bridges. However, the unit CO_2 emissions of some construction materials that are not included in JSCE analysis are calculated according to the PWRI values. The unit cost value is determined according to several cost manuals and the interview.

The similar formulations are used for calculating the environmental impact from both the construction materials and the construction machine during the maintenance and replacement stages. The cost during the construction stage covers the costs of construction materials, construction machine and labor, which are determined according to the design and construction manuals of bridges and the interviews with the practical bridge engineers.

3.2.2 Cost and CO_2 emission in the maintenance stage

In this research, only five bridge components are considered for the lifecycle evaluation, namely the pavement, deck (PC deck and RC deck), painting, expansion joint, and support. They are the major common components available in all studied bridges, but have various characters from one to another. The environmental impact and cost from the maintenance stage contains the environmental impact and cost from both the construction materials and the construction machine, and are formulated in the following equations:

$$E_M = \sum_{i=1}^{5}(E_{iMm} + E_{iMw})\frac{L}{L_i} \tag{4}$$

$$C_M = \sum_{i=1}^{5}(C_{iMm} + C_{iMw})\frac{L}{L_i} \tag{5}$$

where, E_{iMm} and C_{iMm} are the total environmental impact and cost during the maintenance stage from the construction materials for the bridge component i, respectively; E_{iMw} *and* C_{iMw} are the total environmental impact and cost during the maintenance stage from the construction machine for the bridge component i, respectively; and L and L_i are the analysis period and the service life of the bridge component i, respectively.

3.2.3 Cost and CO_2 emission in the replacement stage

The environmental impact and cost from the replacement stage contains the environmental impact and cost from both the demolition of the old bridge and the construction of a new bridge, and are formulated as follows:

$$E_r = E_d + E_c \tag{6}$$

$$C_r = C_d + C_c \tag{7}$$

where, E_d and C_d are the environmental impact and cost due to the demolition of the old bridge, respectively. The environmental impact and cost due to the construction of a new bridge are considered as a part of the environmental impact and cost at the replacement stage, but they are not enclosed if only one lifecycle is analyzed.

The backgrounds, assumptions and limitations for developing these formulas are not discussed in this paper because of their previous publication in this journal (Itoh et al. 2001b). In this regard, the reader should also refer to Itoh et al. (2000a, 2000b, 2001a) for the parametric foundations of unit environmental impact of bridge construction materials and machinery used in this paper.

The calculation values of costs and environmental impacts in the following of this research presented in this paper are in form of the unit area of the bridge deck for the purpose of comparison. In addition, to compare the cost performance, the initial cost of a conventional bridge of each type with certain a span length is given a value of unity. Its environmental impact from the construction stage is also assigned a value of unity. The cost and environmental impact values of both conventional and rationalized bridges are calculated for every 5 years of an interval. A relative index for the cost every 5 years is represented by $C(n)/C_i(0)$. The symbol $C(n)$ is the cumulative cost of the *n-th* year, and $C_i(0)$ is the initial cost of a conventional bridge. Similarly, a relative index for the environmental impact every 5 years is calculated by $E(n)/E_i(0)$. The symbol $E(n)$ is the cumulative environmental impact value for the *n-th* year; and $E_i(0)$ is the environmental impact from the construction of a conventional bridge.

3.3 Effects of Discount Rate on Lifecycle Costs

It is widely discussed that the discount rate has a large effect onto the results of the lifecycle assessment (for example, Kuriyama, et al. 2004). However, it is very difficult to predict the exact values of discount rate at each year within the lifecycle because of the long cycle and the difficulty of the long-term prediction. The effect of the discount rate of 0%, 2%, and 4% after every round of 5 years within the lifecycle of 100 years is shown in Figure 4 in the ratios to the construction cost of a conventional bridge. The service life of 100 years is used in this comparison and the remaining part of this paper. The span lengths of both bridges are 30 m and other data are same as given in the above section 3.1. The lower indices of a minimized girder bridge represent that it is economical over a conventional bridge for each given value of the discount rate.

On the other hand, the commodity prices usually increase year by year due to the inflation, which plays an opposite role in the lifecycle assessment to the discount rate. The increase of commodity price is deemed to counteract the effect of the discount rate and no discount rate is therefore considered in the following part of this paper. In addition, no discount rate is applied in the environmental impact, which is the common approach for the lifecycle environmental assessment at the time being.

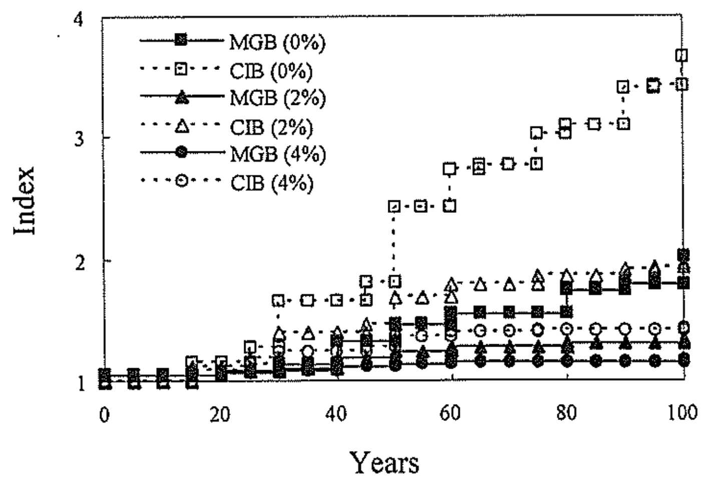


Figure 4. Effects of Discount Rate onto Lifecycle Cost

4. Numerical Results

4.1 LCC and $LCCO_2$ of Conventional and Rationalized Bridges

In the light of the above lifecycle analysis approach, the cost and environmental impact of both conventional I-girder and minimized girder bridges are calculated for every five years and accumulated from the initial construction stage. The conventional I-girder bridge with a span length of 30m is considered as a reference and its construction cost and environmental impact are both assigned to be 1. Other span lengths taken under comparison are 40m, 50m and 60m, and the analysis period is 100 years. Figures 5(a) and 5(b) plot the changes of lifecycle costs (LCC) and lifecycle environmental impact ($LCCO_2$) respectively from year 0 to year 100 for all four bridge span lengths. Without regard to span length, the deviation of conventional I-girder and minimized girder bridges in construction costs and environmental impacts are rather small. However, both costs and environmental impacts of a minimized girder bridge at year 100 are approximately halves of those of a conventional bridge. The main reasons of such a big reduction are the extension of service lives of its components and the decreased requirement of their replacement. In this regard, the cost and environmental impact of a minimized girder bridge in the maintenance stage are drastically reduced compared to the frequent maintenance activities of a conventional bridge.

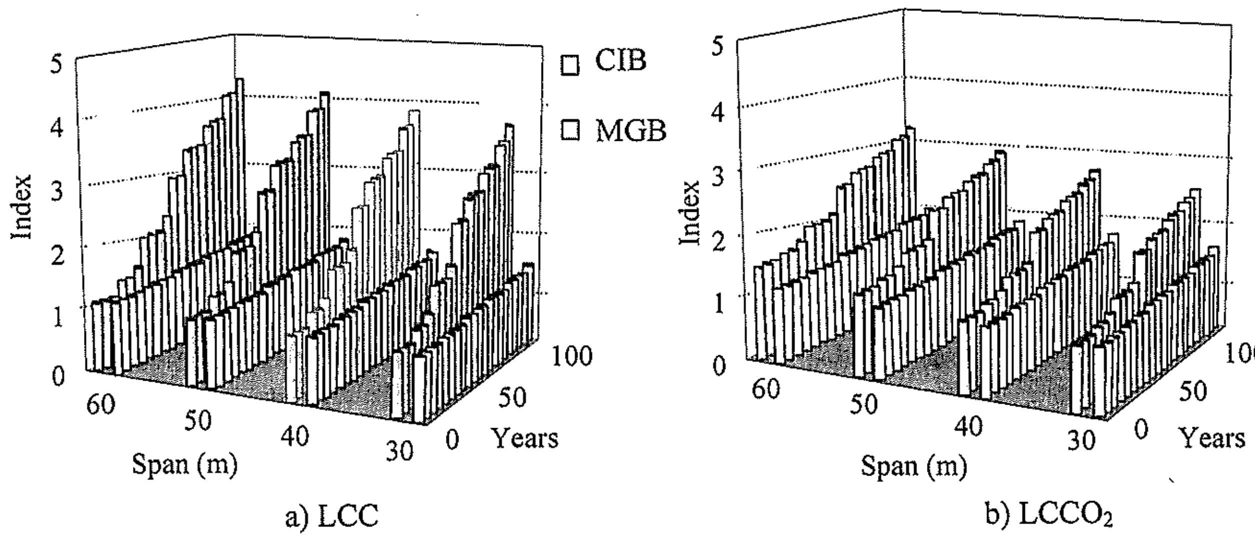


Figure 5. Lifecycle Cost and CO_2 Emission of I-girder Bridges

Figure 6 shows the changes of lifecycle costs and environmental impacts of the conventional, open cross-section box-girder and narrow box-girder bridges from the initial construction stages to the end of analysis period for span lengths of 50m, 60m, 70m and 80m. The cost and environmental impact of a conventional bridge with a 50m span in the construction stage are considered as a basic unit to determine other indices. Similar to a minimized girder bridge, a rationalized box-girder bridge, no matter an open cross-section one or a narrow one, has comparably small values in all costs and CO_2 emission over the analysis period. Without regard to span length, the deviation of costs and environmental impacts between a conventional box-girder bridge and a rationalized box-girder bridge increase from year 0 to year 100. Furthermore, the increasing speeds of LCC are obviously quicker than those of $LCCO_2$ according to this figure. The LCC and $LCCO_2$ values of RBB1 and RBB2 are very close at any time and their changing patterns are very similar. A narrow box-girder bridge has a slightly high LCC and $LCCO_2$ compared to an open cross-section box-girder bridge.

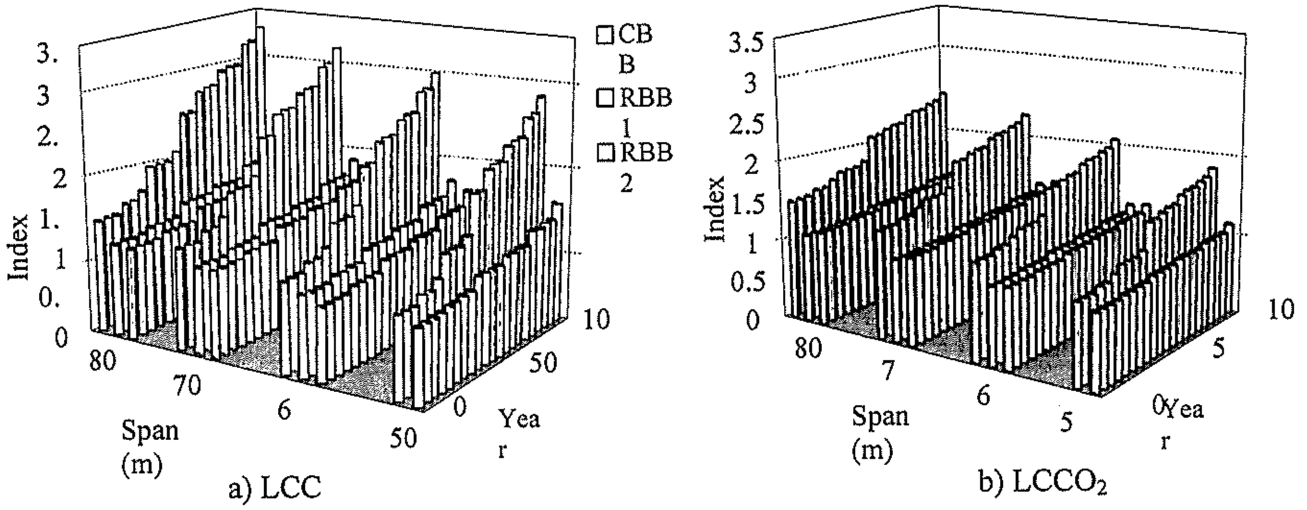


Figure 6. Lifecycle Cost and CO_2 Emission of Box-girder Bridges

Numerical analysis is further carried out for a conventional truss bridge and a rationalized truss bridge. The cost and CO_2 emission of a conventional truss bridge with an 80m span in the construction stage are assigned to be 1. Figure 7(a) and 7(b) show the changes of their lifecycle costs and environmental impacts respectively from the beginning of construction and the end of year 100. The span lengths analyzed for a conventional truss bridge are 60m, 70m, 80m, 90m and 100m. However, only bridges with spans of 80m, 90m and 100m are compared for both a conventional truss bridge and a rationalized truss bridge as the latter is normally designed with a relatively longer span. Similarly, a rationalized truss bridge has a lower lifecycle costs and environmental impacts at any time of the analysis period compared to a conventional truss bridge. For any span length, the gaps between a conventional truss bridge and a rationalized truss bridge in LCC and $LCCO_2$ increase over time. This reflects the long-term effects of maintenance activities in determining the lifecycle costs and environmental impacts.

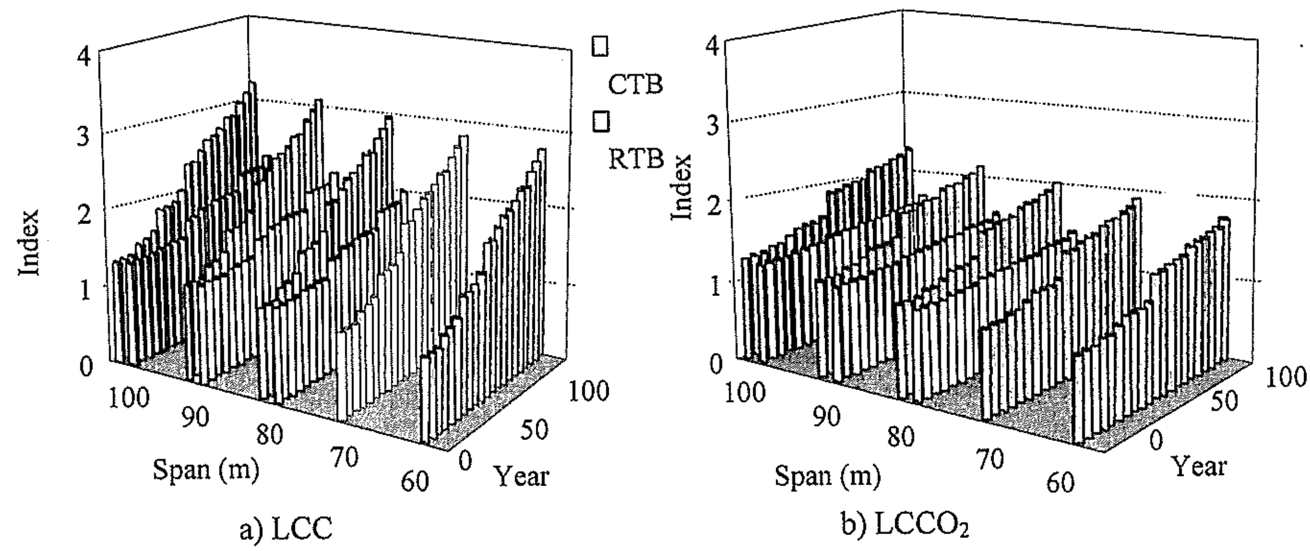
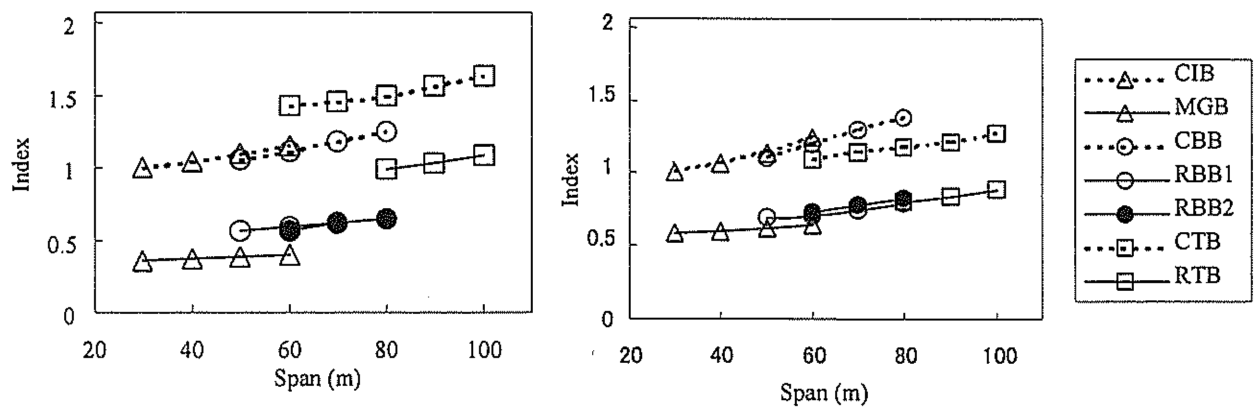


Figure 7. Lifecycle Cost and CO_2 Emission of Truss Bridges

4.2 Effects of Span Lengths on LCC and $LCCO_2$ of Bridges

The span length of a highway bridge affects the economic indicator of a bridge project as well as its safe character. The span length of a bridge needs to be chosen at the initial design stage, which is normally made on the basis of bridge construction experiences. The lifecycle approach conducted in this research makes it possible to study the effects of bridge span lengths in LCC and $LCCO_2$ so that a quantitative relationship between the span length and LCC or $LCCO_2$ can be determined. Figures 8(a) and 8(b) show the LCC and $LCCO_2$ values respectively in year 100 versus the span length for the three types of bridges. The lifecycle costs and CO_2 emission of a conventional I-girder bridge with a 30m span at year 100 are assigned to be 1, and the LCC and $LCCO_2$ of each type of bridges with certain a span length are represented in these figures with relative indices.



a) LCC b) $LCCO_2$

Figure 8. Effects of Bridge Span Lengths in Lifecycle Analysis

As shown in Figure 8, both LCC and $LCCO_2$ of all bridges increase with the extension of the span length with approximately linear relationships. The LCC and $LCCO_2$ indices of three conventional types of bridges are obviously higher than those of rationalized bridges. The LCC indices of conventional and rationalized truss bridges outstand from those of girder and box bridges, but the $LCCO_2$ indices of truss bridges are lower than those of box bridges. The LCC index lines of conventional girder and box bridges are very close as well as their $LCCO_2$ index lines. Similarly, the two rationalized box bridges have close LCC index lines as well as $LCCO_2$ index lines. The minimum girder bridges have the smallest LCC and $LCCO_2$ indices.

Given a linear relationships between the span length and LCC or $LCCO_2$, the approximate slope of each relationship is calculated. Table 3 summarizes the approximate slopes of all types of bridges. Each value represents the approximate increased LCC or $LCCO_2$ if the span length of certain a bridge is extended by a unit. As a whole, the slopes of conventional bridges are bigger than those of rationalized bridges. In other words, compared to the conventional bridges, the LCC and $LCCO_2$ indices of rationalized bridges are less sensitive to their span lengths.

Table 3. Approximate Slopes of LCC and $LCCO_2$ Trend versus Span Lengths

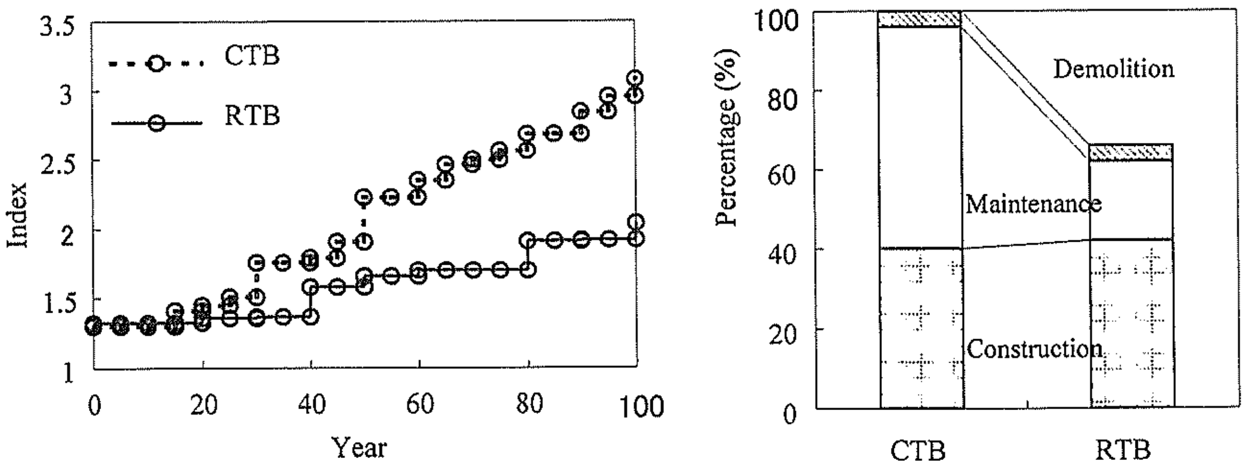
	CIB	MGB	CBB	RBB1	RBB2	CTB	RTB
LCC	1.0	0.22	1.02	0.47	0.67	0.83	0.75
$LCCO_2$	1.0	0.22	1.13	0.40	0.60	0.51	0.51

5. Investigations on LCC and $LCCO_2$ Elements, A Case Study on Truss Bridges

In order to identify the lifecycle costs and environmental impact characteristics of bridges, the above numerical results are further analyzed by investigating the allocations of LCC and $LCCO_2$ elements in all lifecycle stages, especially the effects of maintenance activities. Taking truss bridges as an example, the detailed investigations are reported in the following.

According to the lifecycle costs plotted in Figure 7(a), the LCC changes of a conventional and a rationalized truss bridge with an 80m span are compared in two dimensions in Figure 9(a). Obviously, the indices of the rationalized truss bridge are less than those of the conventional truss bridges especially after a service life of 20 years, and the differences between the indices of the two types of bridges are enlarged with the increase of the service life. Specifically, at the end of the lifecycle analysis (year 100 after construction), the index of the rationalized truss bridge is only 35% of that of the conventional truss bridge.

The lifecycle costs of the conventional and rationalized truss bridges at year 100 are associated with the three lifecycle stages, which are construction, maintenance and replacement stages, and shown in Figure 9(b). The LCC of the conventional truss bridge during construction, maintenance, and replacement stages are about 40%, 56%, and 4% respectively. Given the LCC of a conventional truss bridge as 100%, the LCC of a rationalized truss bridge is only 66%. Furthermore, this percentage consists of 42%, 20%, and 4% from the construction, maintenance and replacement stages respectively. Because of the enhanced design standard of a rationalized truss bridge, its initial construction cost is slightly higher than that of a conventional truss bridge. According to these figures, it can be concluded that the lifecycle cost percentages of a conventional truss bridge in construction and replacement stages are almost equal to those of a rationalized truss bridge. However, the lifecycle maintenance cost of a rationalized truss bridge (20%) decreases drastically compared to that of the conventional truss bridge (56%). As a result, the rationalized truss bridge reduces about one-third of the lifecycle cost of the conventional truss bridge, and this reduction mainly results from the decrease of the lifecycle maintenance cost of the rationalized truss bridge.



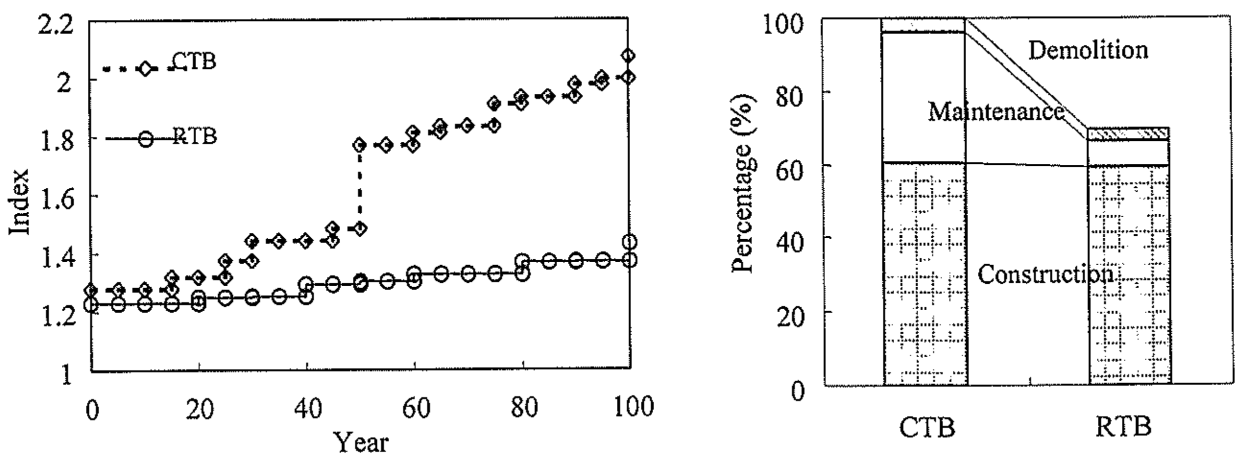
a) LCC Changes of Truss Bridges b) Components of LCC of Truss Bridges

Figure 9. Lifecycle Costs of Truss Bridges

Similarly to the lifecycle cost, the lifecycle environmental impacts of the conventional and rationalized truss bridges are plotted in two dimensions in Figure 10(a) according to the above calculation results shown in Figure 7(b). The indices of the rationalized truss bridge are apparently less than those of the conventional truss bridges from the initial construction stage, which implies that the construction environmental impact of the rationalized truss bridge decreases although its construction cost increases compared to a conventional truss bridge. The differences between the indices of the two types of bridges are enlarged with the increase of the service life, which means that the environmental impact of maintenance activities of the rationalized truss bridge is also less than that of a conventional truss bridge.

At the end of the lifecycle analysis (year 100 after construction), the lifecycle environmental impact of the rationalized truss bridge is quite less than that of the conventional truss bridge. The lifecycle environmental impacts of the conventional and rationalized truss bridges at year 100 are also associated with three lifecycle stages, including construction, maintenance and replacement stages, and their impact values are shown in Figure 10(b). The $LCCO_2$ of the conventional truss bridge in construction, maintenance, and replacement stages are about 60%, 36%, and 4% respectively. Given the $LCCO_2$ of a conventional truss bridge as 100%, the $LCCO_2$ of a rationalized truss bridge is only 69%. Furthermore, this percentage consists of 59%, 7%, and 3% from the construction, maintenance and replacement stages respectively. According to these figures, it can be concluded that the lifecycle environmental impact percentages of a conventional truss bridge in construction and replacement stages are almost equal to those of a rationalized truss bridge. However, the lifecycle maintenance CO_2 emission of a rationalized truss bridge (7%) decreases drastically compared to that of the conventional truss bridge (36%). As a result, the rationalized truss bridge also reduces about one-third the lifecycle environmental impact of the conventional truss bridge, and this reduction mainly results from the decrease of the lifecycle maintenance environmental impact of the rationalized truss bridge.

In addition, compared to the lifecycle cost allocation represented in Figure 9, the construction stage takes an absolutely dominant position in lifecycle environmental impact and its amount does not decrease from the conventional truss bridge to a rationalized truss bridge. The maintenance stage plays obviously different roles in the percentages of lifecycle costs and environmental impacts. One reason is that the manpower takes a large portion of the bridge maintenance cost, but it is not accounted into the environmental impact.



a) $LCCO_2$ Changes of Truss Bridges   b) Components of $LCCO_2$ of Truss Bridges

Figure 10. Lifecycle Environmental Impacts of Truss Bridges

Maintenance activities play a significant role in lifecycle costs and environmental impacts of both conventional and rationalized truss bridges, especially for a conventional truss bridge and in lifecycle cost. Therefore, to reduce the lifecycle cost and CO_2 emissions, the maintenance stage should be paid attention to as well as to the construction stage, and the further study on each maintenance activity becomes necessary. Figure 11 shows the LCC and $LCCO_2$ percentages of six major maintenance activities of the above conventional and rationalized truss bridges. According to this figure, it may be noticed that a maintenance activity may play significantly different role in the conventional and rationalized bridges. For example, the bridge support and deck need frequent replacement for a conventional truss bridge, but they do not need such requirements in a rationalized truss bridge. On the other hand, some maintenance activities such as painting and pavement contribute high portions in both LCC and $LCCO_2$ for both conventional and rationalized truss bridges. In addition, the importance of a maintenance activity in LCC is also different from it in $LCCO_2$. For example, painting is the most important activity in LCC for both CTB and RTB, but deck replacement and pavement contribute the highest portions in $LCCO_2$ of CTB and RTB respectively.

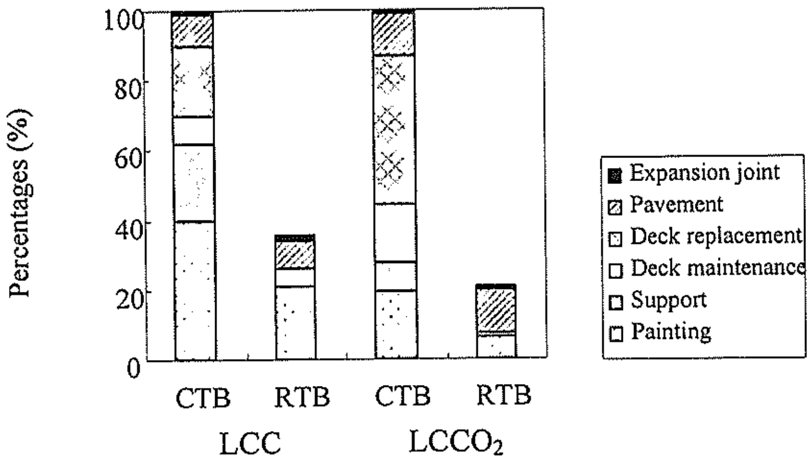


Figure 11. Lifecycle Costs and Environmental Impacts due to Maintenance Activities

6. Conclusions

In this study, a lifecycle analysis approach is applied for bridge technology evaluation. Three newly developed bridge types in Japan, minimized girder bridges, rationalized box-girder bridges and rationalized truss bridges, are investigated in terms of lifecycle cost (LCC) and lifecycle CO_2 ($LCCO_2$) emission. Their numerical results are also compared with those of corresponding conventional bridges with similar environmental conditions. The following conclusions are obtained:

1) The lifecycle cost and environmental impact of a rationalized bridge are less than those of its corresponding conventional bridge. Specifically, the LCC and $LCCO_2$ of the rationalized truss bridge are about two third of those of the conventional truss bridge.
2) Both LCC and $LCCO_2$ of conventional and rationalized bridges increase with the extension of their span lengths. The increasing speeds of a conventional bridge in LCC and $LCCO_2$ are higher than those of its corresponding rationalized bridge. Particularly, the $LCCO_2$ values of conventional bridges are extremely sensitive to their span lengths. These relationships provide a quantitative support in choosing the span length of a bridge during the initial design stage.
3) Construction is a major source contributing both LCC and $LCCO_2$ of a bridge and its proportions in LCC and $LCCO_2$ may however be quite different. In the light of a case study on truss bridges, the

cost and CO_2 emission of constructing a rationalized bridge are almost the same as the construction cost and CO_2 emission of a conventional bridge.

4) Maintenance activities are crucial in LCC and $LCCO_2$ of conventional bridges. A rationalized bridge may highly reduce its maintenance cost and CO_2 emission because of the extended service lives of its components. Particularly, the LCC and $LCCO_2$ of maintaining bridge decks and supports drastically decrease from a rationalized truss bridge to a conventional truss bridge.

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